

A Model Study of the Dynamics of Western Boundary Current/Recirculation System

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LONG-TERM GOAL

My long term goal is to understand the dynamics of the western boundary ocean and its interaction with marginal seas and the general oceanic circulation, and to understand the ingredients necessary to produce a realistic simulation of the variability of the North Pacific and North Atlantic circulation and their interaction with marginal seas.

OBJECTIVES

I have been pursuing my goal in several directions by studying:

- 1) the effects of annual wind migration, thermocline stratification and the north/south width of a wind-driven gyre on the western boundary current/inertial recirculation system;
- 2) the effect of the continental slope on the combined buoyancy-driven and wind-driven western boundary current system;
- 3) the low frequency variability of the thermocline circulation and its application to observations of sea surface height and thermocline temperature anomalies;
- 4) the interaction of the western Pacific ocean and the circulation of its marginal seas and islands in light of the dynamics of coastal Kelvin waves and Rossby waves.

APPROACH

My approach uses the combination of a quasi-geostrophic model, the NRL primitive equation model and analytical theories. Observational data (such as altimeter and upper ocean hydrography data) and model output from more realistic NRL model simulations are also being analyzed in light of the ocean dynamics that we studied. One distinctive aspect of our approach is the close integration of model results, observations and theories.

WORK COMPLETED

1) Western Boundary Current/ Recirculation Dynamics: Following our initial work on recirculation (Liu, 1996a, 1997), more work has been completed toward understanding the effects of the north-south gyre width (Wu et. al., 1998a) and the continental slope (Wu et al., 1998b) in the coupled western boundary current/recirculation system.

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2) Planetary Wave Dynamics: A unified dynamic theory was proposed to interpret various propagation features of the observed interannual and decadal variability in sea surface height (SSH), sea surface temperature (SST) and thermocline temperature (Liu., 1998a, Liu, 1998b, Liu and Shin, 1998, Zhang and Liu, 1998).

3) Coastal Kelvin waves, Rossby waves and the interaction of the Western Pacific Ocean and its marginal seas and islands: Most recently, a great effort has been directed towards the understanding of the interaction among the western Pacific Ocean and its marginal seas and islands. To guide our analysis with better dynamic insights, we first investigated the interaction of Rossby and coastal Kelvin waves in a closed basin (Liu et al., 1998a) and around an island (Liu et al., 1998b; Wu and Liu, 1998a).

RESULTS

1) Western boundary current system: A smaller north/south gyre width is found to significantly intensify the recirculation, because of the increased inertial flow and the associated increase in potential vorticity anomaly along the boundary current (Wu et al., 1998a). This may help to interpret some important features of the recirculation in the North Atlantic and North Pacific. A collaborative effort with NRL is underway to explore quantitatively the related effects in the realistic ocean simulation of the subtropical-subpolar system. It is also found (Wu et al., 1998b) that the buoyancy-driven circulation, by interacting with the continental slope, affects the total transport of the western boundary current dramatically. Instead of resorting to the JEBAR effect which provides little dynamic insight, we studied the deep circulation explicitly and therefore are able to provide direct insights on the interaction between the buoyancy-driven flow and the continental slope.

2) Planetary wave dynamics: Our new theory (Liu, 1998a; Liu, 1998b) highlights different dynamic features between the 1st and 2nd baroclinic modes of the planetary wave: the former is a Non-Doppler shift mode and has its strongest signature in the SSH; the latter is strongly advected by thermocline flow and has its strongest signature in the upper thermocline temperature. Furthermore, in the region of strong westward flow, such as the region of the North Equatorial Current, the two modes are coupled together to produce long wave baroclinic instability. The long wave instability has been confirmed (Singh, 1997) in an eigenvalue calculation using the Levitus ocean climatology as the mean state. Thermocline variability due to instability is also studied in a 500-year run of an eddy-resolving QG model. This long wave instability may be a source of low frequency climate variability. We further studied the forced response of the thermocline to various surface wind stress and buoyancy forcings. The wind forcing is the most efficient in generating the 1st mode, while the surface buoyancy forcing is the most efficient in generating the 2nd mode. Therefore, the observed planetary wave in SSH is most likely to be caused by the wind forcing, while the variability of the upper thermocline temperature is mostly like to be caused by the surface buoyancy variation. A further observational analysis of thermocline variability confirms the coexistence of the two wave processes (Zhang and Liu, 1998). A further numerical study highlights the similarity and differences between subducted temperature and passive tracer anomalies (Liu and Shin, 1998).

3) Rossby wave, Coastal Kelvin wave and the interaction of western Pacific Ocean and its marginal seas and islands: We show that the coastal Kelvin wave produced by an incident Rossby wave on the mid-latitude western boundary is determined by the mass redistribution of the eastern boundary Rossby wave and the incident Rossby wave (Liu et al., 1998a). As a result, the amplitude of the coastal Kelvin wave

is usually smaller than the incident Rossby wave because of the mass spreading from a localized patch throughout the entire basin. The coastal Kelvin wave peaks when the incident Rossby wave peaks on the western boundary. In a basin including the equator, equatorial waves become the dominant mass redistribution process and the resulted coastal Kelvin wave peak substantially later than the incident Rossby wave. This interaction of mid-latitude Rossby and coastal Kelvin waves differs dramatically from that of equatorial Rossby and Kelvin waves.

We further show that the formation of the island circulation can be divided into three stages and can be understood in terms of Rossby and coastal Kelvin waves (Liu et al., 1998b). First, the direction of the island circulation is determined by the wind forced coastal Kelvin wave. Second, the transport of the island circulation is determined by the damped short Rossby wave along the eastern coast of the island. Finally, the pattern of the island circulation is completed after the long Rossby wave from the western coast of the island crosses the basin. For an island on the equator, equatorial Rossby and Kelvin waves play a critical role in establishing the island circulation across the equator (Wu and Liu, 1998a).

IMPACTS AND APPLICATIONS

Our model simulation points out several potentially important aspects in the simulation of the realistic ocean circulation and the boundary currents and its interaction with marginal seas and islands. We are in the process of testing these ideas in collaboration with Dr. H. Hurlburt (NRL) in realistic ocean models.

The interaction between the continental slope, buoyancy-driven flow on the western boundary current and recirculation may explain why the Gulf Stream transport is stronger than the Kuroshio even though the North Pacific has about twice the interior transport than the North Atlantic. Therefore, a correct simulation of the boundary current needs improvement in not only wind forcing and coastal geometry, but also the thermohaline circulation and the continental slope.

The planetary wave study is able to account for a significant part of the observed SSH and SST, which was studied by Dr. Jacobs (NRL). It also explains some important model variability of H. Hurlburt's group in the North Pacific. Furthermore, the wave dynamic nature of the ventilation process ensures that ventilation can be accomplished as an entrainment/detrainment forcing in a layered dynamic ocean model.

The understanding of the interaction between coastal Kelvin waves and Rossby waves provides a powerful dynamic framework to investigate the interaction of the western Pacific Ocean and its marginal seas and islands. This becomes apparent in our recent study of the western Pacific and marginal seas (Wu and Liu, 1998b). For example, the remote response of the SSH around Japan and in the Japan Sea to wind forcing in the central Pacific can be estimated with our analytical theory to within 10% precision as compared with realistic model simulations. This will be our major research direction in the next stage.

TRANSITIONS

We have completed the transition of research focus from western boundary recirculation to the western Pacific marginal seas and islands and their interaction with the western Pacific Ocean. One major task in the next stage of our research is to study the realistic ocean with the Navy model with the focus on

the Japan Sea and the South China Sea. Some idealized dynamics will also be explored to understand the effect of mean advection, nonlinearity and stratification on the interaction of coastal Kelvin waves and Rossby waves. We may also continue to explore the dynamic difference between the Gulf Stream and the Kuroshio systems in light of the buoyancy-driven flow and its interaction with the continental slope.

RELATED PROJECTS

1) We will further strengthen our collaboration with Dr. H. Hurlburt at NRL to attempt to understand the realistic oceanic variability in the western Pacific and its marginal seas and islands.

2) A major effort is made to collaborate with the Chinese Academy of Science (co-sponsored by the Asian Partnership Program of the University of Wisconsin – Madison) to study Chinese marginal seas and their interaction with the western Pacific Ocean. We will collaborate with the QingDao Oceanographic Institution to investigate the East China Sea, the Sea of Japan and their interaction with the Kuroshio; and we will collaborate with the GuangZhou South China Sea Institution to study the South China Sea and its interaction with the tropical western Pacific. Our collaboration is well underway and Dr. DongXiao Wang from the latter institution has been in Madison since July. Collaboration with QingDao Ocean University is also in progress in understanding the dynamics of the South China Sea.

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